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Procedia Technology 14 (2014) 20 – 27
Procedia Technology

2nd International Conference on Innovations in Automation and Mechatronics Engineering, ICIAME 2014

Controlling damping force during aircraft arrestment using self-energized valve mechanism

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Abstract

This paper investigates efforts for controlling damping force during the aircraft landing on aircraft carrier. Since flow through restricted opening ensures damping in any system, the role of a variable orifice is significant. A new self-energized valve mechanism is conceptualized to control the damping force and a mathematical model for energy absorption and then dissipation by means of hydro-pneumatic arresting system is presented. The equation of motion is nonlinear and non-homogenous in nature and has been solved using Taylor's series expansion. Numerical simulation is carried out to extract the performance parameters. The model is capable of predicting the dynamic behavior of the arrester system for variable mass and velocity of landing aircraft. The area of orifice is controlled by self-energized valve mechanism as against contemporary constant run-out control valve. The behavior of arrester system with & without self-energized valve mechanism is compared.

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Keywords: Hydro-pneumatic arresting system; Self energized valve mechanism; Simulation experiments; Aircraft carrier.

Nomenclature

A_o, Q_o, A_{ram}	orifice area, discharge and ram area
C_d , dt	coefficient of discharge and time increment for numerical calculation
F_c, F_{ram}, F_t, F_o	cable, ram, aircraft thrust force and force on valve mechanism plunger

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doi:10.1016/j.protcy.2014.08.004

h, L	valve mechanism plunger travel and half deck pendent length
M_a, M	aircraft mass & combine mass of aircraft and crosshead
N, k	number of reeves and aircraft thrust factor
P_1, P_2, P_o	ram pressure, accumulator pressure and valve mechanism accumulator pressure
W, H	width and height of orifice
X_a, $\dot{X}_a$, $\ddot{X}_a$	run out, velocity and acceleration of aircraft
X_c , V_{ram}	piston travel and ram velocity
γ, ρ	specific heat ration for air and fluid density
θ, Lc	angle of cable with its initial position and cable length over deck
V_1 , $\dot{X}_c$	cable and ram velocity
P_{fi} V_{fi}	accumulator initial pressure and volume
V_{oa}	volume of air inside valve mechanism accumulator
a_o, v_o	acceleration and velocity of valve plunger

1. Introduction

Aircraft generally required long runway for landing, but the same luxury is not available on aircraft carrier. On the aircraft carrier, the maximum available runway length is of the order of 150 m. In order to achieve safe landing, the use of an arresting system is mandatory. Such systems consist of a hydraulic arrangement, which absorbs the energy of the landing aircraft. The damping force is generated by flow of the fluid through restricted opening. The magnitude of this force can be controlled by varying the orifice area. Aircraft arrester systems have received constant attention since last few decades. Since then continual improvements are happening.

Cliff et al. [1] studied the role of constant run out control valve in the arrestment. The experimental reports about hydraulic aircraft arresting gear systems were also published by them. Dmitry et al. [2] used finite element method for modeling of the arresting gear and carried out simulation of aircraft landing using arresting gear. Kaidong et al. [4] studied constant run out control valve device and hydraulic cylinder device, which are two key parts of the arresting system. Kaidong et al. [5] described modeling and simulation of hydraulic aircraft arresting gear.

This paper presents a framework for investigating the dynamic behavior of the hydraulic aircraft arrestor gear system for those aircrafts which land on aircraft carriers. As a first stage of study a model with single degree of freedom has been suggested. The model is capable of predicting the dynamic behavior of the arrester system for variable mass and velocity of landing aircraft. The equation of motion is nonlinear and non-homogenous in nature and has been solved using Taylor's series expansion. The area of orifice is controlled by self-energized valve mechanism as against constant run out control valve. The behavior of arrester system with & without self-energized valve mechanism is compared.

2. System Description

2.1. Construction of Aircraft Arrester Gear with self-energized valve mechanism

The aircraft arrester gear system consists of seven components, viz., a wire rope, set of pulleys, a main hydraulic cylinder assembly, a valve mechanism, an accumulator, set of sheave dampers and a set of cable anchor dampers. The schematic diagram of aircraft arrestment with the hydro-pneumatic system is described in Fig.1(a). A wire rope is laid down across the runway and the same is extended to the main hydraulic cylinder assembly. The same is supported by set of pulleys to provide the desired direction. The wire rope is reeved a number of times on the main hydraulic cylinder assembly to reduce the stroke of piston. A self-energized valve mechanism that connects the main hydraulic cylinder to accumulator is introduced the arrester system. The accumulator is long cylinder having a floating piston with one side of the piston filled with air. A rectangular narrow opening is provided which act as an orifice. A plunger is provided in the valve system whose movement results in changing the orifice area.

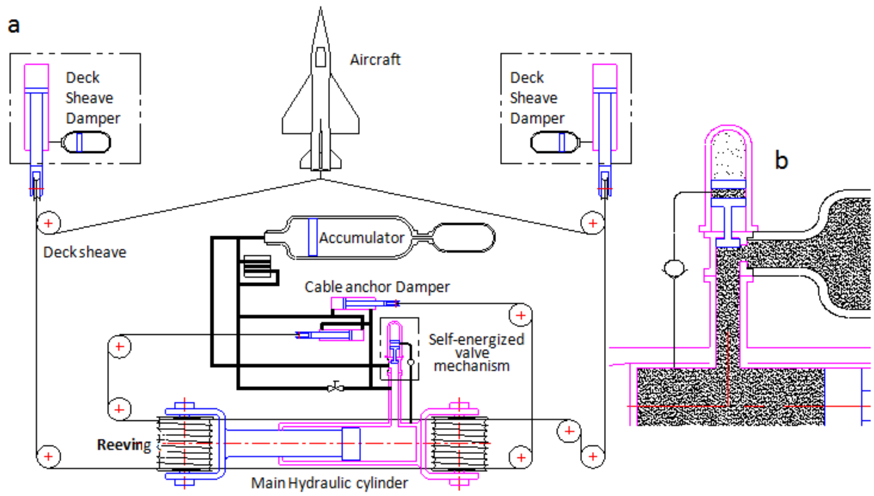

Fig. 1. (a) Schematic of aircraft arrester system; (b) details of self-energized valve mechanism.

2.2. Operation of Aircraft arrester system & energy absorption

On landing, the aircraft engages with the wire rope which is laid down across the runway and pulls it. As the wire rope is reeved on the hydraulic cylinder assembly at the other end, aircraft motion will be transferred to the piston. This motion of the piston will force the fluid into the accumulator via self-energized valve mechanism. This will cause a rise in the pressure inside the accumulator. Since the flow is through a restricted opening, damping force will be generated due to rise in pressure inside the hydraulic cylinder. This pressure can be managed by varying the orifice with the movement of plunger. The plunger movement is achieved by a self-energized valve mechanism as against the conventional constant run-out valve [4, 5, and 6].

2.3. Self-energized Valve Mechanism: Construction and Operation

A schematic of valve mechanism is shown in Fig. 1(b). Valve mechanism consists of a plunger, a floating piston, an accumulator & a pilot line with non-return valve. The movement of the plunger varies the area of the orifice. The accumulator with floating piston is located above the plunger.

As aircraft engages with the wire rope, the movement of piston starts and forces the liquid into the accumulator via a rectangular orifice due to rise in pressure in the main cylinder. This action also causes flow of fluid through the pilot line to valve mechanism accumulator located above the plunger. This flow continues as long as the pressure rise in main cylinder occurs. As the velocity of aircraft slows down due to arrestment, the velocity of the piston also decreases causing reduction in the main cylinder pressure. This reduction creates differential pressure across the plunger and results in a net force on the low pressure side causing the plunger to move downwards. This will result in the reduction of the orifice area thus restricting the fluid flow and causing pressure rise in main cylinder. If the pressure inside the main cylinder will rise more than accumulator, it will result in upward motion of the plunger and hence increase in orifice area. The increase & decrease in the pressure goes on till the complete arrestment and ensures the same maximum pressure during arrestment. The constant maximum pressure will provide the constant damping force & finally constant deceleration. The self-energized valve mechanism will stores the energy when the pressure inside the main hydraulic cylinder increases & utilize that stored energy for the plunger movement when pressure inside the main hydraulic cylinder start reducing.

3. Mathematical Modelling

Based on the working principle of arrestment system, a mathematical model has been developed. In order to simplify the mathematical modeling following assumptions are considered:

- The aircraft is considered as a single point mass,
- Working fluid is incompressible,
- All relative motions are frictionless,
- Inertia of pulleys is neglected,
- Elastic deformation of wire rope is neglected in comparison with aircraft run out distance.
- 1-D planner motion of aircraft with the symmetric loading on wire rope is considered.

For the purpose of mathematical modeling, the free body diagram of system is prepared, Fig. 2. The hydraulic cylinder assembly with the accumulator is replaced by a damper element. x_a is the generalized coordinate for the aircraft motion.

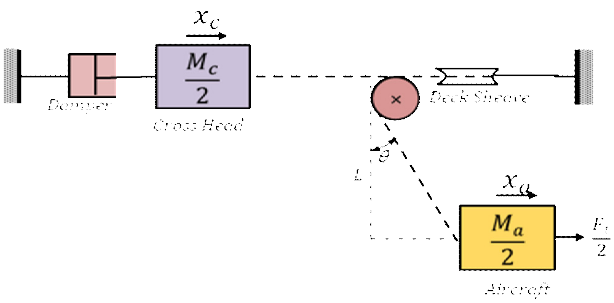

Fig. 2. Schematic representation of arrestment.

3.1. Equation of motion

Writing equation of motion as x_a is generalized coordinate

$$M \times \ddot{x}_a = F_t - (F_c \times \sin\theta) \tag{1}$$

Length of the cable over deck and Angle of cable with its initial position can be written as,

$$L^2 = x_a^2 + h^2 \tag{2}$$

$$\sin\theta = \frac{x_a}{\sqrt{h^2 + x_a^2}} \tag{3}$$

Velocity of cable in terms of aircraft velocity is written as,

$$V_l = \dot{X}_a \times \sin\theta \tag{4}$$

Given, no. of crosshead sheaves and velocity of cable, velocity of ram/cross head is given by,

$$\dot{X}_c = \frac{V_l}{(2 \times n)} \tag{5}$$

At any time of t , L_c is length fed from the hydraulic engine that is transferred to the carrier deck.

$$L_c = L - h = 2 \times n \times X_c \tag{6}$$

At the time of t, ram stroke and its velocity are defined as,

$$X_c = \frac{L_c}{(2 \times n)} \tag{7}$$

Compression of gas in accumulator is assumed as adiabatic compression process and hence gas pressure P_2 is given by equation 8.

$$p_2 = p_{fi} \left[\frac{V_{fi}}{V_{fi} - (A_{ram} \times x_c)} \right]^{\gamma} \tag{8}$$

3.2. Mathematical modeling of valve mechanism

The valve mechanism functions in two different ways based on the movement of the plunger which is operated due to differential pressure across it. If the value of pressure is higher in the main cylinder than of the valve accumulator. Following series of mathematical equation describe the sequence of activities as a result of pressure rise.

$$Q_0(i) = C_d A_0 \sqrt{\frac{2}{\rho}(p_1 - p_o)} \tag{9}$$

$$V_{oa}(i+1) = V_{oa}(i) - Q_0(i) \times dt \tag{10}$$

$$p_o(i+1) = p_o(i) \left[\frac{V_o(i)}{V_o(i+1)} \right]^{\gamma} \tag{11}$$

$$F_o(i) = p_o(i) \times A_c - p_1(i) \times A_p \tag{12}$$

$$a_o(i) = \frac{F_o(i)}{m_p} \tag{13}$$

$$v_o(i+1) = v_o(i) + a_o(i) \times dt \tag{14}$$

$$h_o\left(i+1\right)=h_o\left(i\right)+v_o\left(i\right)\times dt \tag{15}$$

If the main cylinder pressure is lower than of the valve accumulator, then the sequence of activities as a result of pressure drop is described by equations (9), (12), (13), (14), (15), (11) in the said sequence. Based on the travel of plunger the area of orifice can be written as,

$$A_o\left(i+1\right)=W\times\left(H-h\left(i+1\right)\right) \tag{16}$$

From general flow through orifice equation, pressure in hydraulic cylinder can be found out by,

$$p_1=\left[\frac{\rho}{2}\times\frac{1}{C_d^2}\times\frac{Q_0^2}{A_0^2}\right]+p_2 \tag{17}$$

From continuity equation of the fluid flow is

$$Q_0=A_0\times V_0=A_1\times V_1=A_{ram}\times V_{ram} \tag{18}$$

From above two equations, it can be written that,

$$p_1=\left[\frac{\rho}{2}\times\frac{1}{C_d^2}\times\frac{A_{ram}^2}{A_0^2}\times V_{ram}^2\right]+p_{fi}\left[\frac{V_{fi}}{V_{fi}-f.A_{ram}.x_c}\right]^{\gamma} \tag{19}$$

Once pressure on ram is obtained from above equation, Force acting on ram is given by,

$$F_{ram}=p_1\times A_{ram} \tag{20}$$

Since force produced by ram is shared by number of braking cables, the cable force can be defined as,

$$F_c=\frac{F_{ram}}{\left(2\times n\right)} \tag{21}$$

In order to avoid any mishap, in case the landing aircraft fails to catch deck pendent, the aircraft thrust is always kept open during arrestment. This thrust force is given by Eq. 22 as referred by [5],

$$F_t=k\times M_a \tag{22}$$

Acceleration of aircraft can be found out by dividing net force by mass of aircraft.

$$\ddot{x}_a=\frac{1}{M_a}\left\{F_t-\left(F_c\times\sin\theta\right)\right\} \tag{23}$$

Velocity and run out of the aircraft for next instant of time ($t+1$) can be found out by using simple Taylor series expansion with the corresponding values at current time t.

$$\dot{x}_a(i+1) = \dot{x}_a(i) + \ddot{x}_a(i) \times dt \tag{24}$$

$$x_a(i+1) = x_a(i) + \dot{x}_a(i) \times dt \tag{25}$$

3.3. Simulation Modeling

Based on the mathematical model explained in the previous section, a simulation model is constructed using MATLAB [7] and ran on a set of inputs. Some of the input have been extracted from referred article [3-6, 8], while some are generated iteratively. After assigning the suitable inputs to all variables, simulation is carried out.

4. Results and Discussion

The role of self-energized valve mechanism can be appreciated when compared with results in presence of constant orifice valve. Fig. 3. shows the ram pressure and acceleration of aircraft when valve mechanism is absent in the system. The ram pressure increase rapidly, then decreases gradually reducing the damping force and thus the deceleration.

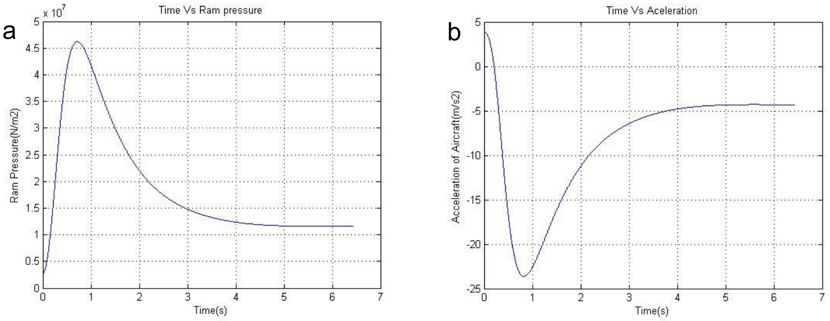

Fig. 3. Performance of arrester without self-energized valve mechanism for (a) ram pressure; (b) aircraft acceleration.

Results (with addition of self-energized valve mechanism) of the simulation are presented in time domain. Fig. 4 (a) shows the aircraft acceleration; it can be observed that the maximum deceleration value is just above –3g. Aircraft velocity is plotted in Fig. 4 (b); initially its value is nearly constant, then decreases rapidly and then decreases gradually till the aircraft is finally arrested.

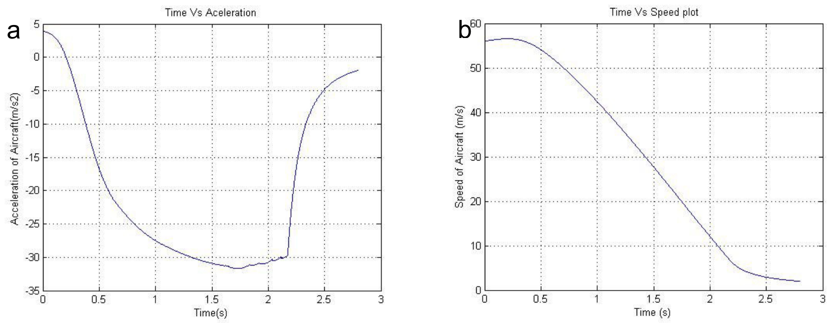

Fig. 4. Performance of arrester with self-energized valve mechanism for (a) aircraft acceleration; (b) aircraft velocity.

Aircraft travel after engagement with wire rope is presented in Fig. 5 (a); it can be noticed that aircraft comes to standstill after travelling a distance of around 85 m. Similar pattern is followed by hydraulic ram travel; its stroke ends well before 3.5 m and is plotted in Fig. 5 (b).

Pressures in hydraulic cylinder and accumulator are presented in Fig. 6. Accumulator pressure keeps increasing while the ram pressure reduces at later stage as the velocity of ram reduces.

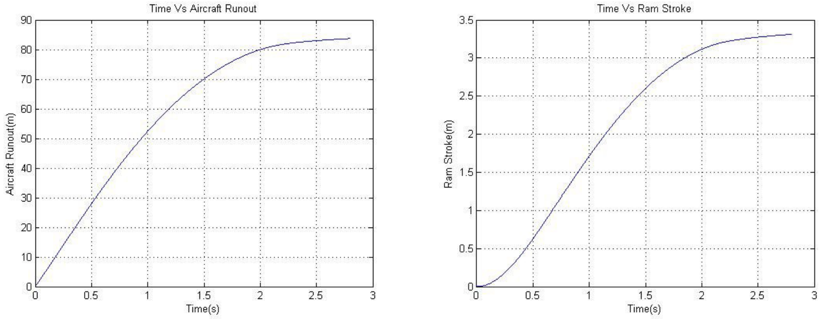

Fig. 5. Performance of arrester with self-energized valve mechanism for (a) aircraft run out; (b) piston travel.

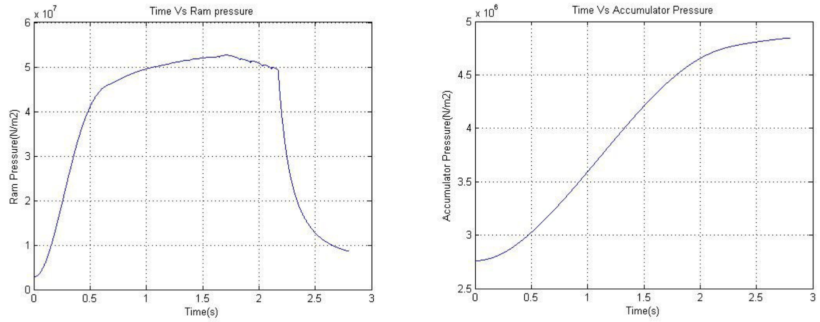

Fig. 6. Performance of arrester with self-energized valve mechanism for (a) ram pressure; (b) accumulator pressure.

5. Conclusion

From the results, it can be seen that a 20 ton aircraft with 56 m/s of landing speed can be stopped safely within a range of 85 m on an aircraft carrier. It is seen that the deceleration of the aircraft depends on the damping force, while the latter depends on the ram pressure. The ram pressure is maintained by self-energized valve mechanism. It can thus be concluded that the self-energized valve mechanism stops aircraft within minimum run out distance and also in reduced time, by keeping maximum deceleration in limit. Further to this, the same model can be used to find out the performance behavior for different combinations of input parameters.

References

[1] Cliff R, Kahn J. Availability and expectation of successful operation of MARK7 arresting gear. US Navy report 1969.
[2] Dmitry M, Igor V, Alexey B. Finite element modelling of the arresting gear and simulation of the aircraft deck landing dynamics. 7th European LS-DYNA conference 2009, Volume E-04-IV.
[3] http://www.globalsecurity.org/military/library/policy/navy/nrtc.
[4] Kaidong L, Zhu Q, Li X. Modelling and simulation for arrested landing of carrier-based aircraft. IEEE International Conference on Mechatronics and Automation, Beijing, China; 2011.
[5] Kaidong L, Zhu Q, Li X. Mathematical model and simulation of a hydraulic arresting gear system. 30th Chinese Control Conference, Yantai, China; 2011.
[6] Liang L, Chen W, Panpan X. Dynamic analysis of aircraft arresting gear based on finite element method. International Conference on System Science, Engineering Design and Manufacturing Informatization; 2011. p. 118-121.
[7] Rudra P. Getting started with MATLAB: a quick introduction for scientists and engineers. Oxford Press; 2009.
[8] Sung W, Shih M, Testing and Modeling for Energy Dissipation Behavior of Velocity and displacement Dependent Hydraulic Damper. Tsinghua Science and Technology: 2008. p. 1-6.